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Integrating Greenhouses into Buildings: A Renewed Paradigm for Circular Architecture and Urban Regeneration

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Abstract: In the post-COVID-19 era, there has been an increasing interest in re-evaluating citizens' living conditions within dense and grey urban areas. The provision of green spaces has always been identified as an important aspect of alleviating contemporary everyday life stress and preventing or limiting mental health-related issues. It is also an important strategy to mitigate urban heat islands and foster adaptation strategies to climate change. Among the numerous experiments of 'green action' available to urban planners, urban farming strategies have been widely used in Europe to provide green spaces and ecosystem services, exploring the topics related to self-production of food, biodiversity, and zero-km cultivation. Therefore, finding new spaces for agriculture in urban environments has driven scientists, researchers, and entrepreneurs to develop new soilless technologies (such as hydroponics, aquaponics, and aeroponics) to maximize yields in urban areas, creating new agricultural and architectural models such as the vertical farms (VF) and the building-integrated greenhouses (BIGH). In this regard, the objective of this paper is to recontextualize the integrated greenhouse element for high-tech food production as new iconic architectural models derived from the experience of the Victorian Winter Gardens and the first tropical greenhouses. Revisiting these perspectives, this paper offers opportunities to redefine the greenhouse as a multifunctional asset that aligns with both environmental goals and architectural standards.

Keywords: greenhouses; urban farming; food security; urban renewal; urban heat island effect; high-tech food production

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1. Introduction

In the post-COVID-19 era, there has been an increasing interest in re-evaluating citizens' living conditions within dense and grey urban areas [1]. Today, we consider the provision of green spaces and the use in urban design of green-based solutions as an essential aspect of alleviating the stress of daily life, improving well-being conditions, and preventing or limiting problems affecting mental health (e.g., burn-out, stress syndrome, etc.) [2]. Additionally, these green-based solutions are excellent for mitigating urban heat islands, preventing flooding, and fostering strategies to adapt to rapid climate change [3]. Nevertheless, the integration of green spaces into urban habitats is not a new concept. It has been extensively studied and researched since the beginning of the first Industrial Revolution, when smoke, pollution, and overpopulation became prominent urban conditions for the first time. In the second half of the XIX century, the anarchist and geographer Eliseè Reclus wrote a contemporary booklet entitled "*Du Sentiment de la nature dans les societies modernes*" [4], where he explored the relationship between modern society and the natural landscape. He concluded that human developments are linked in the most intimate manner to the natural environment and that mankind should be able to enjoy simultaneously the pleasure of arts, culture, and leisure in cities as well as the freedom that they can only find in nature, in its landscapes and vast horizons [5]. A few years later, English architect and urban planner Ebenezer Howard expanded on Eliseè Reclus' ideas. In his 1902 book "Garden Cities of Tomorrow," he proposed new suburban areas connected by railroads and completely immersed in the natural countryside [6]. Howard's garden cities theory was then repurposed by Patrick Geddes throughout the XX century in a period where intense construction and the use of concrete had alienated nature from urban planning practices [7]. Howard and Geddes' ideas proved to be unable to foster the re-naturalization of the living environments. The new homes and urbanizations colonized the rural countryside, acting as a magnet that attracted the nearby big cities, which expanded towards these new towns, devouring the natural landscape in between [8]. The dynamic of saturation and diffusion of urban space, which a few centuries later we would call urban sprawl, was setting in. Eliseè Reclus noticed the danger of colonizing nature, as he wrote: "Unfortunately this movement from the towns to the suburbs has not taken place without disfigurement of the countryside: not only does rubbish of all sorts clutter up the intermediate space between the towns and the country but, an even more serious thing is happening: speculators are taking hold of all the charming sites in the vicinity, they divide them into rectangular blocks, enclose them in homogeneous walls and there hundreds of thousands of pretentious houses are built." Therefore, it is important that today we invert the paradigm proposed by Howard, trying to bring nature and green spaces into the city and integrate them (parks, urban gardens, trees, green walls, and roofs, etc.) within the urban environment instead of colonizing natural land to build our homes and cities. Thanks to contemporary knowledge and technical know-how, it is possible to integrate greenery not only within cities but also within buildings, increasing the density of green spaces in urban areas both horizontally and vertically [9]. In this sense, green spaces are not only used for aesthetic purposes, but they can provide a broad range of ecosystem services that would benefit modern citizens [9].

2. New Paradigms for Urban Green Action

Among the numerous tools of 'green action' available to urban planners and practitioners, urban farming strategies have been widely used in Europe to provide green spaces and ecosystem services since the topics related to self-production of food, biodiversity, and zero-km cultivation are gaining importance. Benefits concerning urban farming involve the possibility of increasing biodiversity in urban areas [10], fostering social inclusion and a renewed sense of self in marginalized neighborhoods [11], improving circularity processes in districts and cities [12], and finally, providing locally and freshly produced food [13]. Furthermore, major global crises that happened in the last five years (such as the already cited COVID-19 pandemic and the Ukraine war) have clearly demonstrated the fragility of our globalized food supply chain, sparking a renewed interest in how to make our cities more resilient to possible shocks within the distribution chain. The complex food chains that bring food into our cities can be subjected to multiple systemic risks where economic, social, or political shocks in one region of the world could influence food distribution and production globally, affecting consumers' behavior and their access to healthy and affordable food [14]. Although the COVID-19 pandemic did not cause a systemic failure, it emphasized the need for systemic change, suggesting that citizens and consumers would accept and support a transition towards more localized supply chains, embracing a systemic shift in the food production, distribution, and consumption stages [15].

Any ecological or energy transition, as well as behavioral changes, cannot occur without strategies that holistically involve all aspects of human life. It is necessary to patiently grow and cultivate a new awareness that leads to a profound revision of one's lifestyle and the economic and consumption models to which we are accustomed. For example, when comparing urban agriculture (UA) to conventional rural agriculture, most studies have focused on environmental factors such as greenhouse gas emissions. This ignores other streams of sustainability and the important social aspects of UA. Research from Hawes et al. 2024 [16] comparing 73 UA sites and 250 rural farms in Europe and the United States showed that the carbon footprint of UA is six times greater than conventional agriculture [16]. A closer examination of the comparison reveals a significant divide between social urban farm projects and commercial rural farms that seem to be incomparable. The data collected also contained significant differences in quality between the two contexts. The UA projects relied on qualitative data through participatory interviews, whereas commercial rural farms predominantly utilize inventory-based quantitative data [17]. Geographic location can also influence emissions outcomes. For example, a comparative study by Sanyé-Mengual et al. 2015 [18] reported emissions of 0.79 kg CO_2 eq per kg of tomatoes produced in an integrated rooftop greenhouse (RTG) on the peri-urban fringes of Barcelona, Spain, compared to 0.87 kg CO_2 eq per kg from rural greenhouse production [18]. However, relying solely on greenhouse gas emissions to evaluate the sustainability of UA can be misleading, particularly when considering yield differences. Community-based UA projects often have lower yields than commercial farms, which increases their environmental impact per unit of food produced [17]. Critics of rooftop greenhouses believe RTGs will not be able to meet commercial-scale demands due to the limited space [18]. Nevertheless, UA and RTGs may pursue goals beyond profits or commercial yields, focusing instead on sustainability by revitalizing underutilized urban spaces and integrating local waste streams into production systems, thereby providing broader societal and environmental benefits [16].

Accordingly, in the transition toward more local and sustainable food systems, new strategies focus on increasing indoor food production in urban areas by utilizing vacant or underused spaces in contemporary cities and metropolises [19]. Finding new spaces for agriculture in urban environments has driven scientists, researchers, and entrepreneurs to develop new technologies that can maximize yields in limited urban spaces. Soilless cultivation techniques (such as hydroponics, aquaponics, and aeroponics) have been well-known production systems for several decades now, but only in recent years have they been moved from rural greenhouses into urban areas creating new agricultural and architectural models such as the vertical Farms (VF) and the building-integrated greenhouses (BIGH) [20]. The advantages of the integration of agricultural systems within buildings and urban areas (neighborhoods and districts) are not only connected to the possibility of producing food without occupying precious and expensive urban grounds but also to the way they could implement synergies between the built environment and agriculture [21]. A simulation study by Chen et al. (2024) [22] demonstrated that BIGHs operating under a Nonlinear Model Predictive Control (NMPC) framework consistently achieved energy cost savings compared to stand-alone buildings. The NMPC leverages dynamic models to optimize control decisions, effectively reducing CO_2 emissions and energy expenses. The study analyzed 11 cities across diverse climate zones, moisture regions, and seasons, highlighting the importance of monitoring key parameters such as temperature, humidity, CO_2 levels, and lighting to ensure the successful growth and fruiting of plants in BIGHs [22]. If these parameters are not monitored, then consequences such as delayed growth, reduced fruit production, and fungal infections could occur. The NMPC continuously controls these factors by controlling HVAC systems, pad cooling, blinds, fans, lighting, CO_2 levels, humidity, and temperature. The synergies between energy, CO_2, and moisture between the building and the rooftop greenhouse are constantly being exchanged. In BIGHs, CO_2 flows from the building, where human respiration elevates CO_2 levels, to the greenhouse to be utilized by the plants in photosynthesis, reducing CO_2 by 52 kg/m^2 through building integration [22]. Additionally, heating and cooling can be exchanged between the two structures, ensuring comfort for office workers and promoting plant growth. The study concluded that integrating BIGHs with buildings under NMPC control can achieve a 15.2% overall reduction in control costs, including energy and CO_2 management, demonstrating its potential as an efficient and sustainable solution for urban environments [22]. It is important to note that each city will have its own unique parameters and requirements to develop RTGs that operate efficiently, achieving a balance in the symbiosis between the buildings and the RTG.

Integrating agricultural systems re-establishes a direct connection to local food sources, reducing reliance on large-scale retailers that import even native varieties from distant countries. Many of these large farms focus their entire capital on producing monoculture. Monoculture farming leads to significant environmental drawbacks such as reduced habitat heterogeneity, negative impacts on pollinators, and increased vulnerability to pests and disease. If these large-scale farms are impacted by any form of shock, this can impact the city's ability to receive crops or drastically increase prices [14]. By having local food production in BIGHs, cities can ensure food security and enhance urban resilience. Additionally, BIGH can alleviate skepticism about the quality of indoor and off-site food production.

Accordingly, visible production and architectural models that integrate local farming systems into urban landscapes can disseminate new production technologies, educate citizens on healthy local diets, and highlight the environmental benefits of these practices. Integrating food-productive greenhouses into buildings can be seen as a renewed greenhouse model, driven by the iconic images of the Victorian ages when available technologies of glass and steel paved the way for the Winter Garden models. For the first time, tropical plants and greenery were integrated into buildings and cities. This paper acknowledges the significant interest within the scientific community in integrating food production systems within buildings and districts to provide fresh food and greenery in cities. Instead, it focuses on the contribution to the physical manifestation in the territory through the architectural model of the greenhouse element rather than on the production and its technical aspects. Indeed, greenhouses and transparent enclosures have historically possessed aesthetic value, serving both functional and cultural roles. However, the advent of intensive enclosed agriculture has often relegated greenhouses to utilitarian constructs, primarily associated with production-oriented, non-aesthetic purposes. This paper seeks to challenge this paradigm, emphasizing the greenhouse as a distinct architectural typology characterized by a rich history, specific design principles, and evolving technical innovations. By recontextualizing greenhouses as architectural entities, their integration into urban environments can be enhanced, enabling sustainable and localized food production while contributing to urban aesthetics.

3. The Greenhouse as New Contemporary Architectural Model

The principles of urban agriculture now find architectural declination through two main models: (i) integrated hydroponic greenhouses and (ii) new vertical farms [9]. Large, high-tech vertical farms aim to maximize production and ensure smooth operation. Similar to new urban factories, they are often hidden underground or in the suburbs, where land is cheaper and more available, or in unused and abandoned industrial complexes. The agricultural production of vertical farms obeys the rules of good functioning. For this reason, they prefer separation to contamination over other typical urban activities and thus greatly dilute their own potential to regenerate the urban environment.

Conversely, the integration of building and production systems is epitomized by the widespread adoption of greenhouse models. These greenhouses, abstracted from their productive function, serve as sites of social exchange and consumer awareness, fostering environmentally and health-conscious communities. The greenhouse, originally utilitarian, has evolved into a versatile and influential typology in contemporary architecture. Nineteenth-century greenhouses, such as the winter gardens of Vienna and Brussels, were splendid structures for the care and cultivation of native and exotic plants. These iron and glass structures were intended to accommodate nature, and there are excellent examples in Vienna and Brussels (Murphy, 15). Its austere industrial aesthetic, as a structure for agricultural production, makes it suitable to assume a symbolic and regenerative role.

Modern greenhouses are used as social spaces where people can meet, interact, and share experiences related to nature and food. Some urban regeneration projects, for example, use greenhouses as spaces for community events, local markets, and educational activities. They also serve as places of consumer awareness, where people can buy and consume local and sustainable products, facilitating a direct link between production and consumption.

Many cities have integrated urban greenhouses into food markets to offer fresh, locally grown products to their residents. Additionally, many historic botanical gardens are transforming their greenhouses into spaces related to food and nutrition as a place to educate and raise awareness about sustainable eating, as represented by the Jardin des Plantes de Paris [23]. Here, the École de Botanique (Botanical School) offers both students and the public a chance to discover the diversity of plants from all the temperate regions of the globe, from flowering plants to ferns and mosses and from dwarf herbaceous plants to shrubs.

Modern greenhouses with industrial and functional characteristics contribute to the design of new urban landscapes that reflect sustainability and environmental appeal on the architectural scale. Looking back in time, projects such as the Crystal Palace, which once represented the advancement in engineering of its time, are now reinterpreted with an aesthetic that comes 'from below,' as described by Bernard Rudofsky in his work on architecture without architects [24]. Thus, modern greenhouses are not only spaces for agricultural production but also symbols of social communication and consumer awareness. Through austere industrial aesthetics, these structures play a key role in urban regeneration and the promotion of sustainable lifestyles, shaping new, environmentally and health-conscious citizens.

In this regard, extensive research has been conducted in modeling and simulating diverse facets of greenhouse design. A range of tools is currently available for evaluating simulation-driven environmental metrics, such as solar radiation, water utilization, and specific energy models. Additionally, these tools also assess the impact of heating, ventilation, and air conditioning (HVAC) systems on crop loads, further enhancing the comprehensiveness of greenhouse design simulations [25]. These distinct greenhouse components are being integrated into more cohesive systems as greenhouse designs develop. The main force behind this integration is the requirements of Building-integrated Agriculture (BIA), which frequently calls for a variety of coupled configurations and requires exact optimization parameters for successful integration within urban buildings [26,27].

While BIGH is a relatively new addition to the urban landscape, the concept of urban agriculture itself is well-grounded and widely supported. However, there is a disconnect between the architectural community's willingness to embrace urban agriculture and the lack of research engagement in this domain. This disconnect necessitates a bridge between architectural practice and research to foster a more holistic understanding of greenhouse integration. A comprehensive analysis of the systems and design considerations involved in greenhouse integration is crucial for shaping effective design methodologies [28].

3.1. A Brief History of Greenhouse Architecture

In the first century, Lucius Junius Moderatus Columella and Gaius Plinius Secundus, two renowned Roman agricultural scholars, referenced the existence of proto-greenhouses—dubbed 'specularia'—constructed specifically for Emperor Tiberius (42 BCE–37 CE). These greenhouses, presumably located adjacent to Tiberius's Villa Jovis on the Isle of Capri, a tourist attraction even today, served a unique purpose. According to Gaius Plinius Secundus's account in his Natural History (Book 19, Chapter 23), the specularia featured beds mounted on wheels, which could be rolled out into the sunlight or retracted beneath glazed frames during winter months, utilizing transparent stones for insulation [29]. The beds were rolled outside on sunny days, and when it was cold or during winter, they were retracted back into the frames for year-round growing [29]. These greenhouses were designed to cater to the emperor's exceptional fondness for a particular delicacy: snake melons, a traditional vegetable crop grown in the lower Galilee and the Palestinians, which he could then enjoy daily [29].

In the 17th and 18th centuries, France used structures known as orangeries to protect fruit plants from severe winter temperatures [30] (Figure 1, see Appendix A for further details). These structures, with lofty brick walls and broad southern glass windows, made it easier for sunlight to enter. During the harsh winter months, pot-grown fruit plants, in particular oranges, were placed in these structures for protection and warmth. The orangeries were also exported during the colonization of the Americas, where one structure still exists today, the Wye House in Maryland. It is the oldest surviving orangery in the United States, where recent research has suggested that agricultural experiments for medicinal and food plants were conducted [31]. In the nineteenth century, Europe saw the birth of massive glasshouse conservatories, which were particularly built to nurture exotic tropical plants obtained from foreign nations [32].

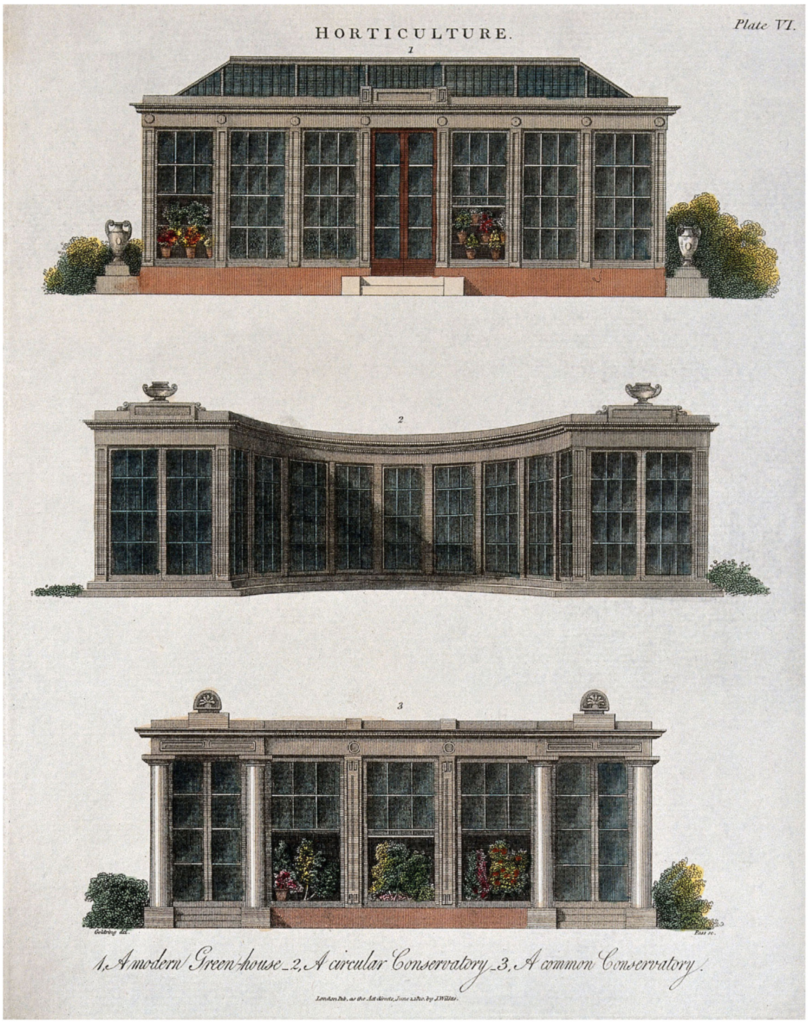

Figure 1. Types of orangeries. Colored engraving, Wellcome Collection, London. Source: Wellcome Collection. The image shows three typologies of orangeries, namely: (1) a modern greenhouse; (2) a circular conservatory; (3) a common conservatory.

The Victorian era stands as the epitome of the greenhouse boom, characterized by landmark structures such as Chatsworth's Great Conservatory (1840), the Palm House now at Kew Gardens (moved to Kew Gardens in 1848), and the iconic Crystal Palace's Great Exhibition (1851). The greenhouse, therefore, serves as a poignant symbol: a testament to both humanity's impact on the planet and the birth of modern climate control efforts. Moreover, the introduction of the Wardian case (named after its creator Nathaniel Bagshaw Ward, who, after years of experimentation, debuted the case at the Great Exhibition in 1851) revolutionized plant cultivation, demonstrating how artificial environments can foster growth while also hinting at the potential perils of such manipulation [33].

As shown in Figure 2, the Wardian case is a plant-protective container that is hermetically sealed. The container's tight glazing resulted in minimum air exchange, allowing for a delicate balance of heat, light, and air, as well as a cycle of condensation and evaporation with little moisture loss. The glass case, as illustrated by Ward in *On the Growth of Plants in Closely Glazed Cases* (1842), is frequently seen bathed in beams of sunlight and represents an ideal habitat. The cases are separate models put in space. They spatialize fictions of benevolent, plentiful nature that humans can carefully cultivate [33].

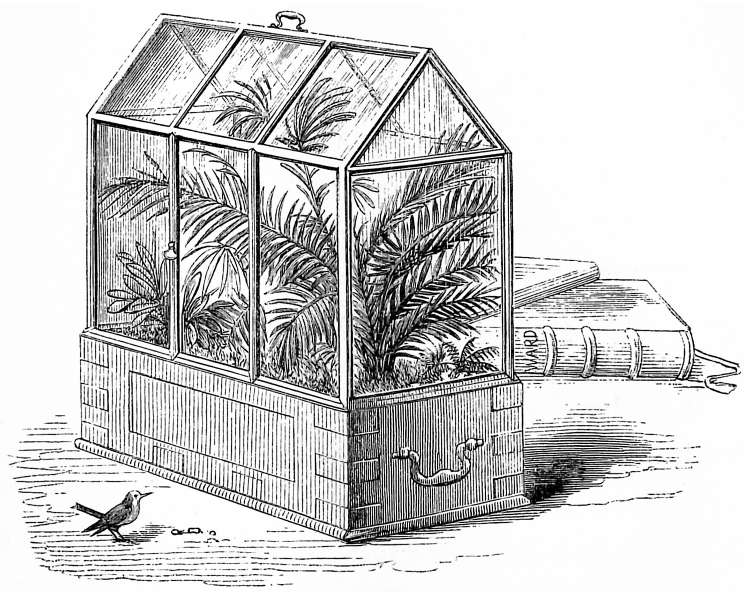

Figure 2. Wardian Case by Nathaniel Bagshaw Ward. Credits: © On the Growth of Plants in Closely Glazed Cases.

During the Victorian era, the Wardian case emerged as a groundbreaking tool for botanical experimentation and climate manipulation. This miniature Eden allowed for the precise control of air quality and environmental conditions, transcending natural constraints to foster plant growth. Ward even drew parallels between his case and the Primordial Garden, highlighting his ambition to not just replicate but enhance nature. His vision extended to urban applications, suggesting that such refined climates could benefit large towns, offering a perpetual summer against the vagaries of weather. In a similar vein, John Claudius Loudon revolutionized conservatory design with socially integrated spaces. These architectural marvels provided a tropical oasis within urban settings where the elite could relax amidst lush greenery. Loudon took his concepts further by proposing grandiose glass structures that could modify vast areas, realizing a fantasy of halting seasonal variations. Both visionaries saw technology as a means to transform metropolitan climates, paving the way for projects like the Jardin d'Hiver in Paris, which embodied their shared dream of melding controlled environment agriculture practices with city life [33].

Dustin Valen explores how Victorian science was transmitted into building culture through horticulture and how this affected architectural creation in nineteenth-century England in his book *On the Horticultural Origins of Victorian Glasshouse Culture*. Here, Valen delves into the intricate relationship between horticulture and architectural production in 19th-century England. By translating Victorian scientific principles into architectural culture, he unearths how horticulture profoundly shaped the built environment. The analysis highlights the pivotal role of books and gardening periodicals in disseminating scientific and environmental ideologies. Furthermore, Valen scrutinizes how horticulturists' conceptualization of 'artificial climates' was reframed in the context of human health, ultimately evolving into the concept of 'medical climates' in architectural design [34]. This evolutionary trajectory offers a unique perspective on the intersection of horticulture, science, and architecture in the Victorian era.

The innovative application of greenhouse technology has driven the integration of urban agriculture and the built environment, putting it at the forefront of multidisciplinary convergence. This technology not only bridges the gap between architectural practices and scientific understanding but also demonstrates how mechanical developments may be used to address environmental issues [34]. As a result, this integration has heralded a new age in urban settings, in which buildings, rather than immobile shelters, actively promote sustainability and productivity, transforming the urban landscape [27].

Over the centuries, transparent architectural structures have emerged, reflecting humanity's evolving relationship with the natural world. We can define some typological macro-sets based on their primary function or a combination of several functions:

1. **Greenhouses for agri-food production:** Crop growth is the greenhouse device's oldest and most widespread function. It aims to maximize agricultural production by optimizing climatic parameters and protecting crops from climatic variations. There is a wide choice of greenhouses for agricultural purposes that are made of slender metal structures and plastic sheeting in their most elementary and inexpensive solution [35]. This type often occupies immense portions of land, as in the now well-known case of the Almeria region, which covers more than 250 square kilometers and is known as the 'sea of plastic.' Their use is exclusively agricultural, and they are of little interest to the purposes of this discussion. From an architectural perspective, the most interesting configuration of this greenhouse typology is represented by the Dutch-style steel and glass greenhouses or similar, which, with their architectural consistency, lend themselves to a multiplicity of uses [36].
2. **Contemplative, decorative, and educational greenhouses:** Epitomized by botanical gardens and the orangery, these edifices primarily serve aesthetic and scientific purposes, cultivating ornamental, exotic, or rare plant species for display. Botanical gardens have functioned as learning centers, fostering intellectual discourse and social interaction among visitors. Architecturally, they resembled the magnificence and wealth of the grand royal palaces or nobility through the language of glass and iron. The example of exotic and distant architecture often inspired decorative parties. The decorative function of greenhouses is a precious and alive heritage [37]. Many throughout Europe incorporate decorative motifs cast in iron, exhibiting architectural dignity through the integration of decorative motifs cast in iron, as the famous Serres D'Auteuil in the Bois de Boulogne in Paris (end of the XIX Century) (Figure 3), the Palmenhaus in the Schönbrunn Palace Park in Wien, the Royal Greenhouses in Laeken, the Temperate house in the Kew Royal Botanical Gardens in London or the Tepidarium Roster in Florence, Italy. Like many others, these structures aim to grow tropical or exotic plants while enhancing the visual appeal of their surroundings.

Figure 3. Serres d'Auteuil. Palmarium—Jardin botanique de la Ville de Paris—France. Credits: © Salix/Wikimedia Commons.

Their enduring legacy manifests in contemporary institutions like the renowned Hortus Botanicus in Amsterdam (Figure 4). The institution was founded in 1638, and in 1993, following the palm greenhouse built at the beginning of the XX century, Zwart and Jansma designed the new three-climate greenhouse. It was conceived as a modern and iconic landmark where the visitor is led through different climates, from the desert to the tropics.

Figure 4. Three-climate Greenhouse, De Hortus, Amsterdam. Credits: L. Zaffi, M. D'Ostuni.

3. **Hybrid and Indefinite Greenhouse Spaces**: The Crystal Palace, originally erected in London's Hyde Park for the Great Exhibition of 1851, stands as a seminal example of this typology. Its reconstruction in Sydenham in 1854 (Figure 5) marked a shift from the traditional greenhouse model, transforming it into a hybridized, ambiguous space where vegetation enveloped the interior. As Murphy astutely observes, this shift in function contributed to the Crystal Palace's gradual descent into "slow oblivion" [38]. Kousidis attributes the combination of uninterrupted glass surfaces and vegetated interior spaces to their ability to present themselves as a new type of urban public space with a collective and shared dimension [39]. The fascination with these structures is undoubtedly related to their spatial potential, but it is probably equally due to their ability to evoke, regardless of their functions, interactions with the natural environment or, as in the case of R.B. Fuller's geodesic inventions, a new universal vision [40].

Figure 5. The "Crystal Palace" from the Great Exhibition at Sydenham. Colored process print, ca. 1861, Wellcome Collection. Source: Wellcome Collection.

3.2. The Evolution of Contemporary Urban Greenhouses and Indoor Food Production

The evolution of greenhouse architecture reflects the dynamic interplay between humanity's desire to connect with nature and the continuous reinterpretation of architectural forms to adapt to changing cultural values and technological advances. There are numerous contemporary examples, from far-flung ones such as Rafael Moneo's Atocha Station Tropical Garden in Madrid (1992) to the more recent and innovative bioclimatic designs of the Eden Project in Cornwall, UK (opened in 2001) or the sustainable strategies employed in the Pyramide Inversée in Amsterdam (completed in 2015), which underscore the enduring relevance of this architectural typology in addressing pressing environmental challenges and promoting harmonious coexistence with the natural world. There are numerous contemporary examples that underscore the enduring relevance of this architectural typology in addressing environmental challenges and promoting harmonious coexistence with nature. Furthermore, the advancement in cultivation techniques, as well as the development of more efficient lighting technologies and climate control systems, allow plants to thrive in harsh urban conditions today. Accordingly, thanks to newly consolidated soilless techniques (hydroponics and aeroponics), it is possible to increase yields of food crops on small urban surfaces, opening up a new world of possibilities for the integration of Controlled Environment Agriculture (CEA) into buildings [9]. As such, researchers and practitioners have developed a fourth greenhouse model:

4. **Soilless productive greenhouse:** This greenhouse takes advantage of new production systems like hydroponics, aeroponics, or aquaponics and mixes them with new technologies such as artificial LED lighting and indoor climate control systems (HVAC) to maximize yields in limited urban spaces [10]. Hydroponic production is a method of growing plants in a soilless medium that dates back to ancient civilizations. However, with the advancement in modern technology, hydroponics has evolved into an effective way of growing indoor plants (Figure 6). Vertical agriculture is a method of growing plants in layers in a vertical arrangement, usually in an urban environment [9]. It aims to increase agricultural yields and conserve land and water resources [12]. Vertical farming usually requires complex technical equipment and facilities, such as irrigation systems, light regulation, and temperature control equipment.

Figure 6. Research Greenhouse with Hydroponics Agriculture at the Department of Agricultural and Food Science. University of Bologna, Italy. Credits: L. Zaffi, M. D'Ostuni.

Greenhouse cultivation has traditionally relied heavily on locally sourced soils, such as loam enriched with organic matter, for container-based crop cultivation. However, the inherent challenges of soil-based mediums—including their substantial weight and the necessity for sterilization—led to heightened costs and operational difficulties. The advent of hydroponic farming techniques revolutionized commercial greenhouse yields by introducing a paradigm shift towards soilless agriculture [32]. Hydroponics utilizes sterilized organic or inorganic substrates that effectively retain moisture and nutrients, or nutrient-dense solutions, to foster plant growth. The advantages of hydroponics are numerous, including regular fertilizer availability, a sterile root zone, accurate nutrient delivery to plants, and faster plant movement. These benefits have considerably increased the efficiency and productivity of commercial greenhouse operations [32].

The origins of hydroponic farming date back to the 17th century when scientists began to understand that soil primarily serves as a conduit for chemicals and water essential for plant growth. Woodward's pioneering experiments with mint plants in various water sources, including the Thames River and rainwater, demonstrated that plant growth was impeded in the absence of solutes [41]. Julius von Sachs further advanced the field with his nutrient solution method, utilizing a wide glass tube equipped with a cork stopper to cultivate plants. The crucial role of elements such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur for plant growth was elucidated by Justus von Liebig, laying the groundwork for modern hydroponic techniques [42]. The identification of micronutrients like iron, manganese, boron, zinc, copper, and molybdenum between 1860 and 1938 further enriched the understanding of plant nutritional needs. Gericke's seminal work led to the coinage of the term "hydroponics" in 1937 for the method of growing plants in water enriched with nutrients [43]. Hoagland and Arnon from the University of California built upon this foundation with extensive research, publishing bulletins that contributed significantly to the public and industry's understanding of hydroponics [44].

NASA's extensive research over the past three decades has driven the advancement in hydroponic technology. With growing interest in cultivating plants on the International Space Station and during future missions to other planets, hydroponics has become essential for astronauts to provide fresh produce and air purification. To mitigate the risks of soil dust inhalation and machinery contamination, NASA has led research initiatives on nutrient uptake in hydroponic systems and the real-time monitoring of nutrient concentrations in mineral nutrient solutions [32]. NASA's research findings have been widely implemented in commercial hydroponic greenhouses worldwide. The United States is expected to witness a significant expansion in hydroponic operations, with an estimated 2480 facilities by 2026, according to IBIS World [45]. This growth underscores the enduring importance of hydroponics in the future of agriculture and space exploration, as it provides a sustainable and controlled method of crop production, essential for both terrestrial and extraterrestrial.

Concerns about food production, processing, consumption, and transportation have become increasingly pressing due to the dynamics of urban expansion and development. A growing number of scholarly and professional domains are becoming interested in sustainable urban food production [46]. The incorporation of Rooftop Greenhouses (RTGs) into urban structures is becoming increasingly popular as a practical way to enhance urban green spaces and develop new agricultural districts. These RTGs use soilless cultivation methods atop rooftops to support public and private agricultural operations, such as growing fruit trees and fragrant plant cultivation. The customized use of RTGs offers enormous possibilities because of the wide variations in climate patterns and building styles around the world. Thus, it is essential to construct pilot projects in order to verify the energy-efficient and economical advantages of integrating RTGs into urban environments. These programs are invaluable testing grounds for assessing the benefits and viability of incorporating RTGs, which helps to ensure the long-term growth of urban agriculture [47].

With the increase in urbanization and the growing demand for locally sourced food, urban agriculture (UA) is positioned to play a critical role in our cities. While the present trend in UA use in metropolitan areas is changing, it frequently exists on low-cost property, such as city-owned or publicly leased facilities, that help with municipal expenses [48]. Projections predict that food production in Controlled Environments Agriculture (CEA) for UA will expand to places with significantly greater prices than rural equivalents [8]. However, pricing may not be the only challenge when implementing RTGs. Municipal laws, regulations, and fire codes could hinder the implementation of RTGs. Engineers must consider the weight and structural demands the RTG may impose on the building. Reinforcements or modifications to the building can be costly but would be necessary to avoid future risks or damages to the overall structure. It may also be more difficult and time-consuming to transport supplies to the rooftop than in traditional agriculture. In addition, RTGs may also be in direct competition with other renewable energies, such as photovoltaics [49]. As RTGs and rooftop usage grow in popularity, it will be necessary for cities to define laws and regulations that include calculations for rooftop integrity.

According to Nemali (2022) [32], there are several potential future directions of greenhouse technology on the industry's current challenges. As climate change raises global temperatures, greenhouse food production is poised to become a crucial component of the world's food supply chain, particularly in temperate regions. Simultaneously, efficient cooling technologies are anticipated to be further developed for warmer climates as an efficient mitigation response to global warming. The evolution of greenhouse automation is anticipated to foster the development of increasingly sophisticated systems. Internet of Things (IoT) sensors are expected to facilitate real-time monitoring of plant growth and biochemistry. This will enable autonomous and localized decision-making and environmental optimization to boost crop yield, quality, and nutritional value [50].

In the future, greenhouses are expected to prioritize minimizing their carbon footprint by significantly reducing fossil fuel consumption and bolstering their reliance on renewable energy sources. Furthermore, to address the pressing issue of declining freshwater resources in numerous regions, advancements in water-use-efficient technologies are likely to be embraced. These evolving trends underscore the greenhouse industry's commitment to sustainability, efficiency, and adaptability to meet global environmental challenges. These efforts are crucial for ensuring a secure and resilient food production system for future generations.

4. From Theory to Practice: Urban Greenhouses as Regenerative Models of Buildings and Urban Spaces

As we have seen, there is a multiplicity of factors underlying the current fortunes of the greenhouse architectural model in urban contexts ranging from social to food production, environmental, and much more. Greenhouse models have symbolic values and are complemented by their exceptional adaptability, making them suitable for a wide range of applications. From being a design object for domestic interiors to large-scale urban projects, the greenhouse model proves its versatility and practicality.

The greenhouse, a symbol of modern green sensibilities, is a simple structure that spans different scales, essentially consisting of an exposed structural skeleton and a transparent covering. Its architectural style, as defined by Valerio Paolo Mosco, is 'bare, clean, unadorned and simplified" [51], falling squarely into the category of modern and contemporary architecture. It embodies the charm and beauty that, as Giovanni Michelucci described, are characteristic of architecture born out of necessity. Its technical and constructional peculiarities partly contribute to its success and popularity. Typologically, it is an easily reproducible modular organism conceived in terms of a system and components. It is a model marked by the criteria of lightness, ease, rapidity of assembly, disassembly, temporariness, integrability, sustainability, and minimal impact on soil or buildings. Greenhouses are highly adaptable to different technical and climatic requirements. Through a wide selection of greenhouse accessories such as sunscreens, transparent surface treatments, opening skylights, and photovoltaic additions, they are able to provide versatility.

Moreover, the greenhouse is a model of "democratic" architecture, which is affordable architecture for all. A greenhouse can be the product of a refined architectural design and built by a specialized firm, but it can be in the simplest versions, easily self-built, or purchased in assembly kits through e-commerce channels. A greenhouse can be the result of craftsmanship or an industrial supply chain like any other object on the market, making it extremely widespread and widely available, instilling its accessibility.

For these reasons, the greenhouse model also finds multiple uses in the built environment and urban regeneration actions. The incorporation of new functions with a new symbolic apparatus can be conducted quickly, cheaply, and lightly but also easily reversible. Certainly, climatic conditions and elements of local architectural tradition or culture significantly impact the spread of greenhouse buildings. For these reasons, the most interesting examples and applications, both historically and in contemporary times, are rooted in the geographical area of Northern Europe. Among them, the Netherlands has always been one of the most interesting study grounds for the attention paid to the technical, typological development of greenhouses. Specific climatic factors (e.g., reduced daylight hours in certain seasons) and the need to maximize agricultural production have led to the development of fully glazed greenhouses. These are known globally as Dutch-style or Venlo greenhouses, named after their place of origin.

Today, it is easy to find examples of the versatile use of this type of structure in the Netherlands. Due to the difficult geological conditions, the Netherlands first explored and developed an intensive, soilless, artificial-light-dependent indoor cultivation. As already mentioned, the Dutch Venlo-style greenhouses have brought forward the concept of traditional greenhouses to implement yields and efficiency for their crops. In this regard, the Netherlands represents a unique case study to evaluate how contemporary greenhouses can be integrated into the built environment. These are hybrid constructions where the use of greenhouses is often limited due to the different microclimatic needs required for various functions, such as plant cultivation and human occupancy. This type of architectural element can be considered a manifesto of catering related to vegetable self-production and quality food. There is also a vital branding component that reflects widespread and emerging sensibilities. In Amsterdam, Mediamatic [52], located along the banks of the IJ, utilizes a series of greenhouses of varying sizes to support its food production and cultivation activities, enabling the provision of a fully plant-based menu. This greenhouse typology operates at multiple scales, including intimate dining experiences for two within small greenhouses positioned adjacent to the canal. The approach integrates the supply chain with an experiential gastronomic-spatial dimension, blending culinary experimentation, art, culture, and politics (Figure 7).

Figure 7. Mediamatic. Greenhouses for growing vegetables and for dinner. Amsterdam. Credits: L. Zaffi, M. D'Ostuni.

De Kas (the greenhouse in Dutch) [53] is a small temple of upscale sustainable dining that has sprung up in Frankendael Park. The greenhouse, which started as a shelter for exotic plants around 1920 and was abandoned in the late 20th century, was in danger of demolition. Restored and converted in the early 2000s, it houses a sizeable scenic restaurant hall and is part of the restaurant's cultivation according to the motto "picked in the morning, consumed in the afternoon" [54]. De Kas shows how these spaces allow nature and urbanization to merge (Figure 8). The modern greenhouse serves as a transition zone between the built and the natural, connecting the urban environment with the natural. The austere, industrial aesthetic of the modern greenhouse, derived from its productive function, has become a symbol of a new indigenous and ecological style.

Figure 8. De Kas, Amsterdam. The main greenhouse and the productive area. Credits: L. Zaffi, M. D'Ostuni.

In Amsterdam, the flat roof of an unknown 1970s building underwent a remarkable transformation into a bar and meeting place (the Zoku) [55]. The lightness of the glazed greenhouse systems allowed a new volume to be built directly on top of the existing structure. Glazed spaces alternate with open spaces populated with herbs, creating a modern and exciting meeting place. Under their characteristics, greenhouses are progressively populating low-rise buildings, giving them a new quality and attractiveness and exciting urban planners and architects alike (Figure 9).

Figure 9. Zoku.The addition of greenhouses on the rooftop of the anonymous modernist-style block in Amsterdam. Credits: L. Zaffi, M. D'Ostuni.

In Utrecht, "The Greenhouse" [56] is a two-floor greenhouse for catering built during the redevelopment plan for the areas around the central station. On the upper floor, the crops are housed in a recurring pattern illuminated with photovoltaic-powered LED systems, while the lower part of the building contains eating spaces (Figure 10).

Figure 10. The greenhouse. The addition of greenhouses on the rooftop of the anonymous modernist-style block in Amsterdam. Credits: L. Zaffi, M. D'Ostuni.

In Haarlem, above the degraded multi-story parking lot De Kamp near the historic center, a greenhouse has been built to house the café-restaurant De Dakkas [57] (the greenhouse on the roof in Dutch). The place with open spaces for growing herbs provides a pleasant setting in contrast to the grayness of the structure on which it stands (Figure 11).

Figure 11. De Dakkas. The restaurant and event hall greenhouse on the roof level of the parking building, Haarlem. Credits: L. Zaffi, M. D'Ostuni.

It is not uncommon to see greenhouses standing out on top of newly constructed buildings as symbolic elements of the new generation. The HoogIJ Greenhouse [58] is situated on the roof terrace of a new office building in a new development area in Amsterdam Noord. Close to Hoogtij's tall orange watchtower. The greenhouse hosts taste, musical, and cultural events in a natural and dynamic environment with a panoramic view of Amsterdam and the IJ River. It complements the activities and offices of the hub building, which is dedicated to young and innovative enterprises (Figure 12).

Figure 12. HoogIJ Greenhouse on the rooftop at Amsterdam-Noord. Credits: L. Zaffi, M. D'Ostuni.

5. Conclusions

Integrating greenhouses within urban buildings may represent a transformative shift towards sustainable city living and resource-conscious design, fostering urban food system transition. The evolution of the greenhouse, from its inception as a controlled environment for exotic plants to today's multifunctional urban growing enclosure, reflects the potential for these spaces to support not only food production but also community-building and environmental resilience. This integration has roots in early glasshouses of the Victorian era, such as the Crystal Palace, and has evolved significantly, aligning with contemporary priorities of urban sustainability and localized food production.

As urbanization intensifies, the architectural model of greenhouses incorporated into building designs, or Building-Integrated Greenhouses (BIGH), can offer a number of advantages: (i) enable food production within city boundaries, (ii) reducing dependence on long-distance supply chains, and (iii) fostering food security in urban areas. This model not only mitigates environmental impacts but also offers economic and social benefits, including job creation, increased biodiversity, and improved air quality. BIGH structures serve as conduits for community engagement, where spaces traditionally reserved for aesthetic purposes are reimagined for urban agriculture, educational activities, and social exchanges. They embody a practical approach to regenerative urban design, reintroducing greenery into dense urban areas without compromising precious ground space.

Technological advancements in soilless cultivation methods—such as hydroponics, aquaponics, and aeroponics—play a pivotal role in the success of modern urban greenhouses. These methods allow greenhouses to thrive in constrained spaces, using minimal soil and water resources while optimizing yields. As cities adopt these high-tech solutions, the future could see greenhouses acting as essential components in the urban fabric, integrated into residential, commercial, and mixed-use buildings.

Looking forward, further interdisciplinary research is essential to bridge gaps between architecture, agriculture, and technology, ensuring effective greenhouse integration within buildings. A key success component will be to effectively reuse buildings' resources to cultivate food crops in enclosed environments [12]. In a linear economy, outputs from buildings, such as heat, CO_2, water, and nutrients (in the form of wastewater), are almost impossible to recover. Instead, BIGH can work as an on-site tertiary treatment, maximizing resource use efficiency for urban food production. In this sense, engineers, urban planners, architects, and agronomists should be trained to work together to overcome construction/economic challenges [59]. Enhanced simulation tools and design methodologies will improve greenhouse efficiency by optimizing energy use, resource management, and crop productivity. In warmer climates, new cooling technologies and advancements in HVAC systems will also be crucial to maintaining optimal growing conditions and responding to global warming while further reducing energy consumption.

Further research is also needed to understand BIGH's operating procedures and practical management. The high-tech food production system that these systems require cannot be easily managed by the inhabitants of common urban buildings (either office or residential buildings). Important research questions such as who the next generation of urban farmers is and how those farmers can access farming spaces in private buildings should be raised when planning the BIGH project.

Ultimately, the BIGH concept has the chance to redefine and reshape urban green spaces, transitioning from passive landscapes to active sites of production, education, and community involvement. This approach aligns with circular economic principles, where urban structures contribute directly to their surrounding environment. By embedding agriculture within architecture, it could be possible to pave the way for greener, more resilient cities that support local food systems and encourage urban self-sufficiency.

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Appendix A

Table A1. Overview of greenhouse and orangery figures with location, year built, and source information.

Figure Number	Description	Location	Year Built	Source and Credits
Figure 1	Types of orangeries	London, UK	Early 18th century	Colored engraving, Wellcome Collection. Source: Wellcome Collection
Figure 2	Wardian Case by Nathaniel Bagshaw Ward	London, UK	1842	On the Growth of Plants in Closely Glazed Cases, 2nd ed., John Van Voorst, p. 71
Figure 3	Serres d'Auteuil Palmarium—Jardin botanique de la Ville de Paris	Paris, France	1895–1898	© Salix/Wikimedia Commons
Figure 4	Three-climate Greenhouse, De Hortus	Amsterdam, The Netherlands	1993	L. Zaffi, M. D'Ostuni
Figure 5	"Crystal Palace" from the Great Exhibition, installed at Sydenham	London, UK	1851 (relocated 1854)	Colored process print, ca. 1861, Wellcome Collection. Source: Wellcome Collection
Figure 6	Research Greenhouse with Hydroponics agriculture	Bologna, Italy	2010s	Department of Agricultural and Food Science, University of Bologna. L. Zaffi, M. D'Ostuni
Figure 7	Mediamatic: Greenhouse for vegetables and private greenhouses for dinner	Amsterdam, The Netherlands	2000s	L. Zaffi, M. D'Ostuni
Figure 8	De Kas: Main greenhouse and productive area	Amsterdam, The Netherlands	Original: 1927 Repurposed: 2001	L. Zaffi, M. D'Ostuni
Figure 9	Zoku: Rooftop greenhouses on modernist-style block	Amsterdam, The Netherlands	2016	L. Zaffi, M. D'Ostuni
Figure 10	The greenhouse: Rooftop addition on a modernist-style block	Amsterdam, The Netherlands	2016	L. Zaffi, M. D'Ostuni
Figure 11	De Dakkas: Restaurant and event hall greenhouse on parking building rooftop	Haarlem, The Netherlands	2017?	L. Zaffi, M. D'Ostuni
Figure 12	HoogIJ Greenhouse, rooftop	Amsterdam Noord, The Netherlands	2018?	L. Zaffi, M. D'Ostuni

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